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(54) **OPTICAL DEVICES WITH NANOWIRE GRID POLARIZER ON A CURVED SURFACE AND METHODS OF MAKING AND USING**

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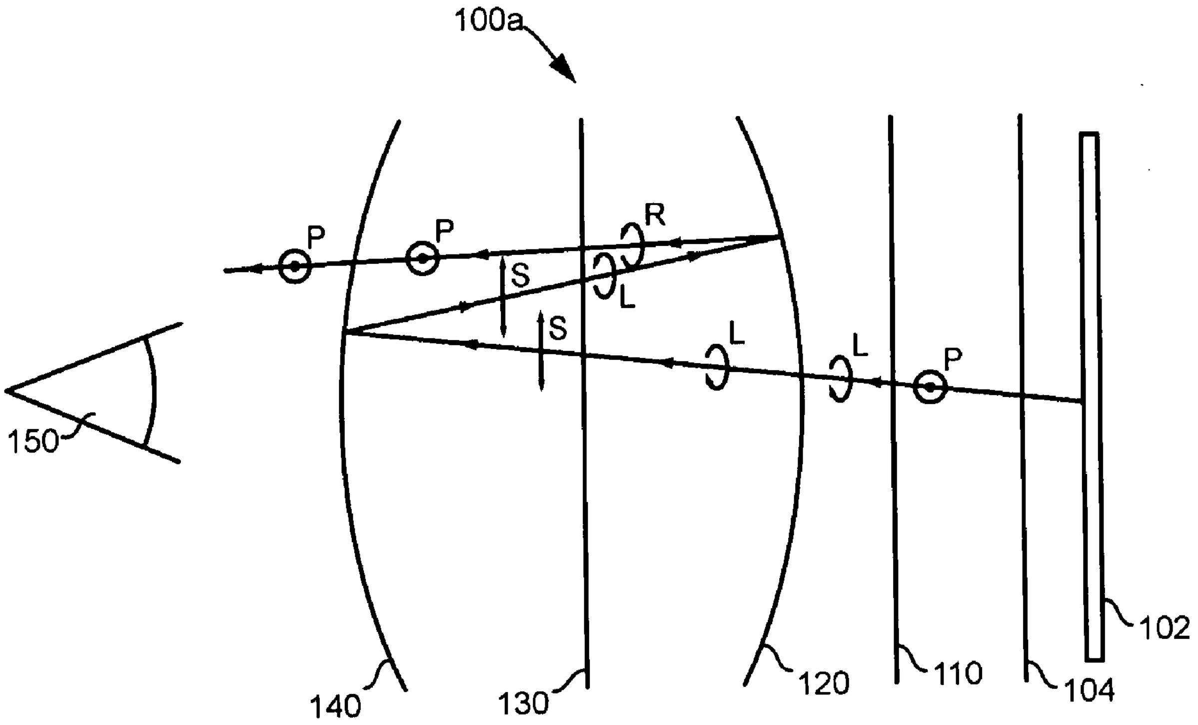
(57) **ABSTRACT**

An optical device may include, in order, a first quarter wave plate; a half mirror; a second quarter wave plate; and a curved nanowire grid polarizer. The curved nanowire grid polarizer may include a curved substrate, a non-regular, substantially periodic array of substantially parallel, elongated nanoridges disposed on the curved substrate and having a wave-ordered structure and being oriented along a first direction, and an array of metal nanowires disposed on the array of nanoridges



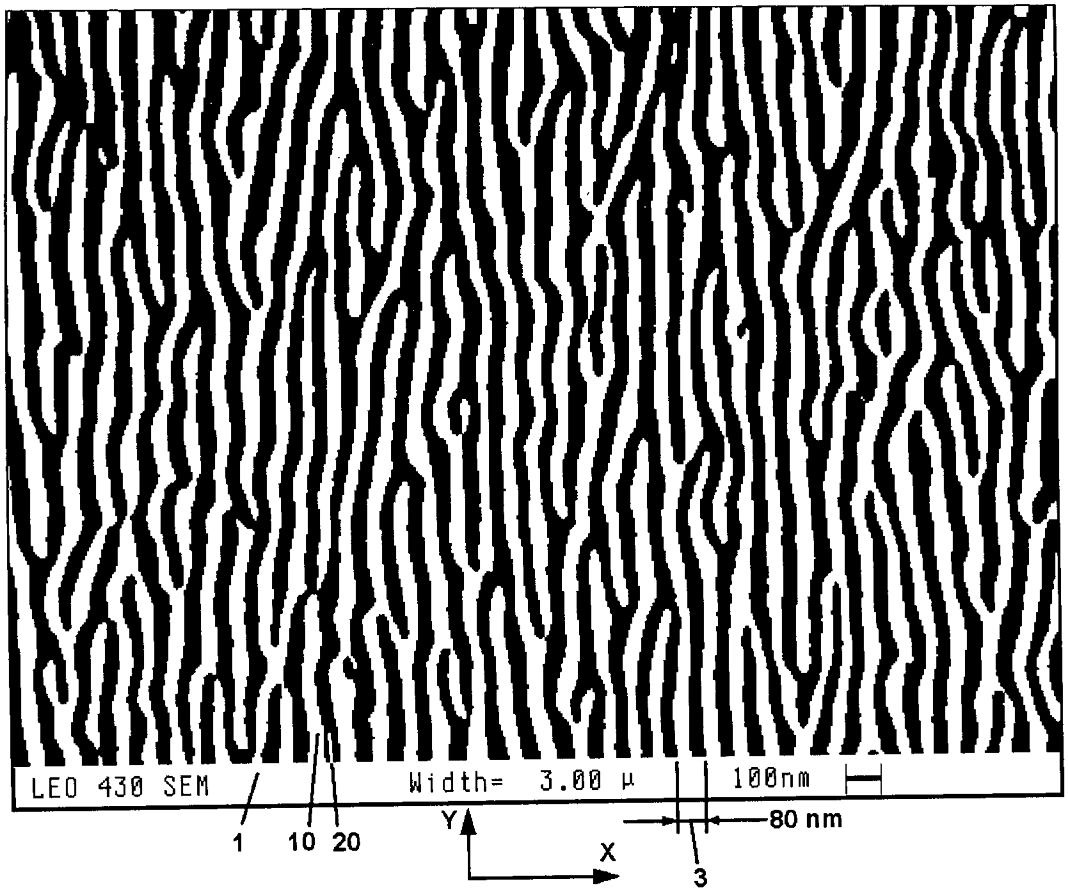


FIG. 1A

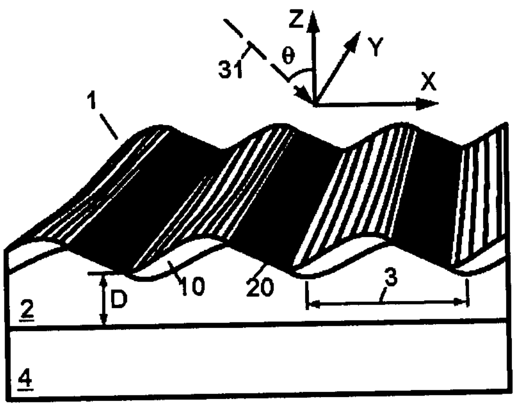


FIG. 1B

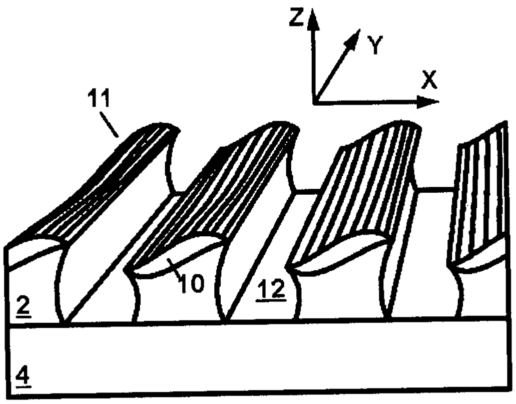


FIG. 1C

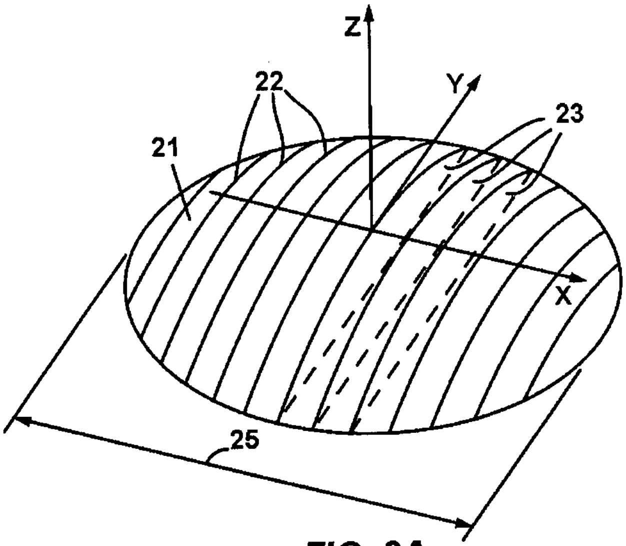


FIG. 2A

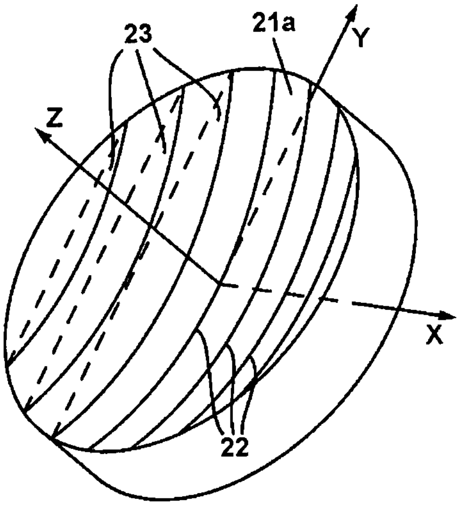


FIG. 2B

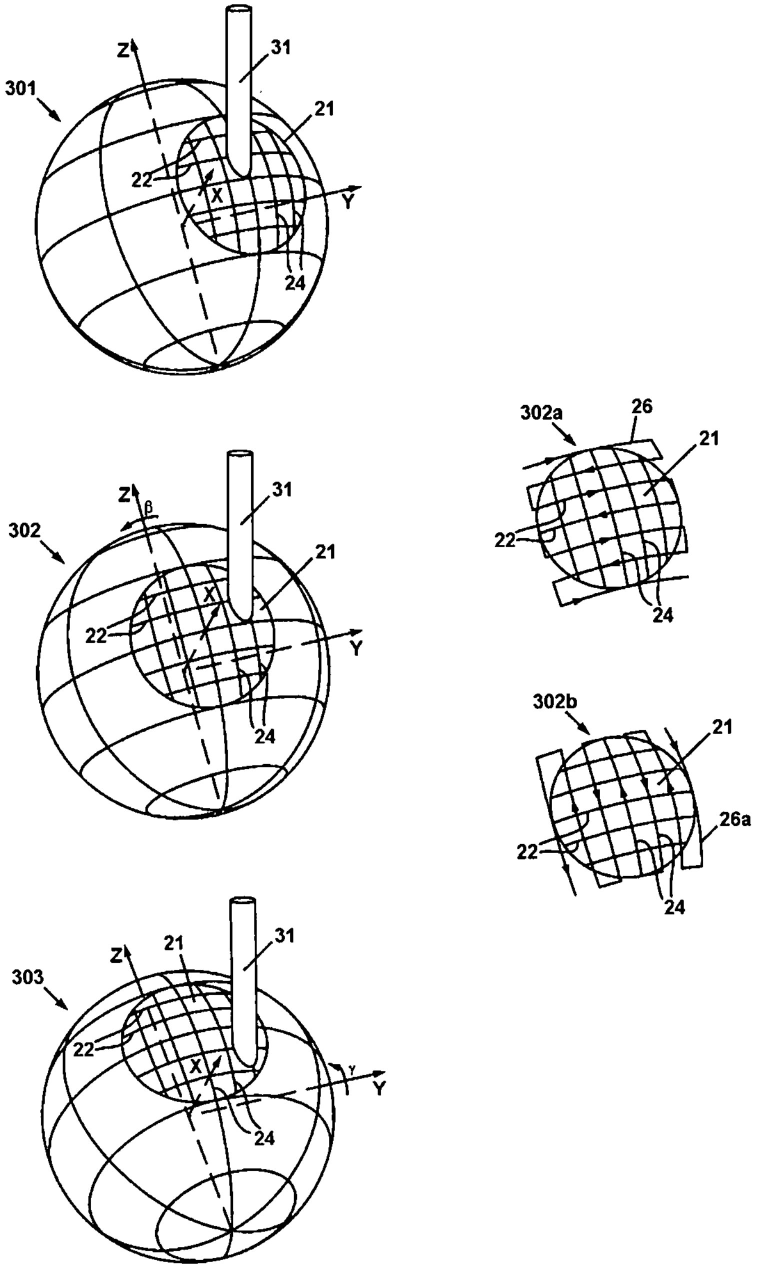

301
Z
31
21
22
X
Y
24
302
Z
β
31
21
22
X
Y
24
302a
26
21
22
24
302b
21
26a
22
24
303
Z
21
31
22
X
γ
Y
24

FIG. 3

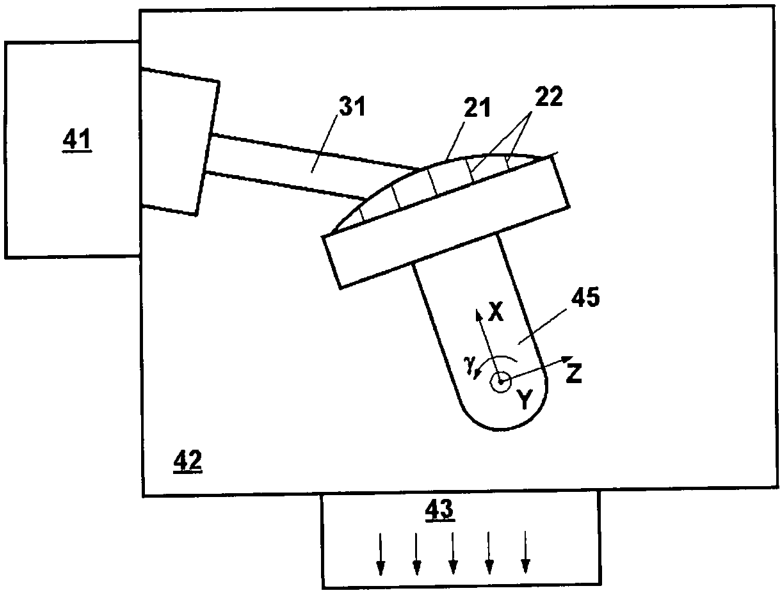


FIG. 4

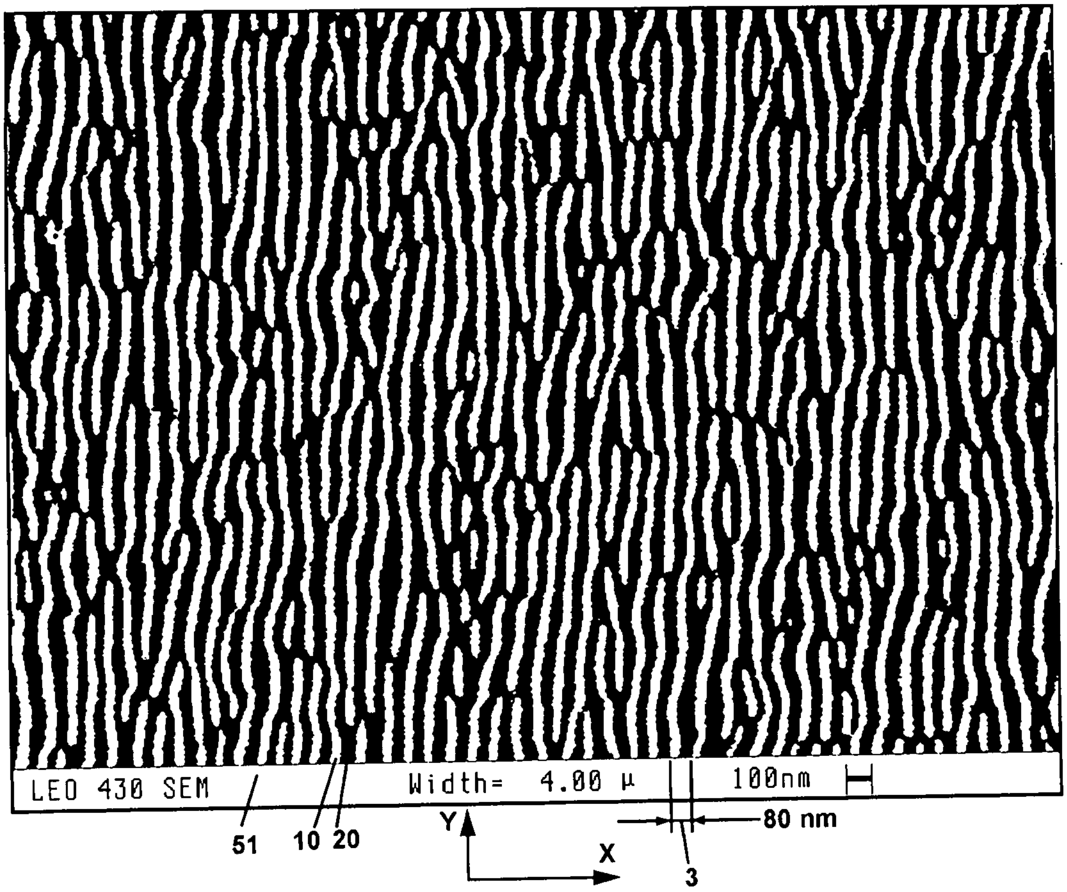


FIG. 5

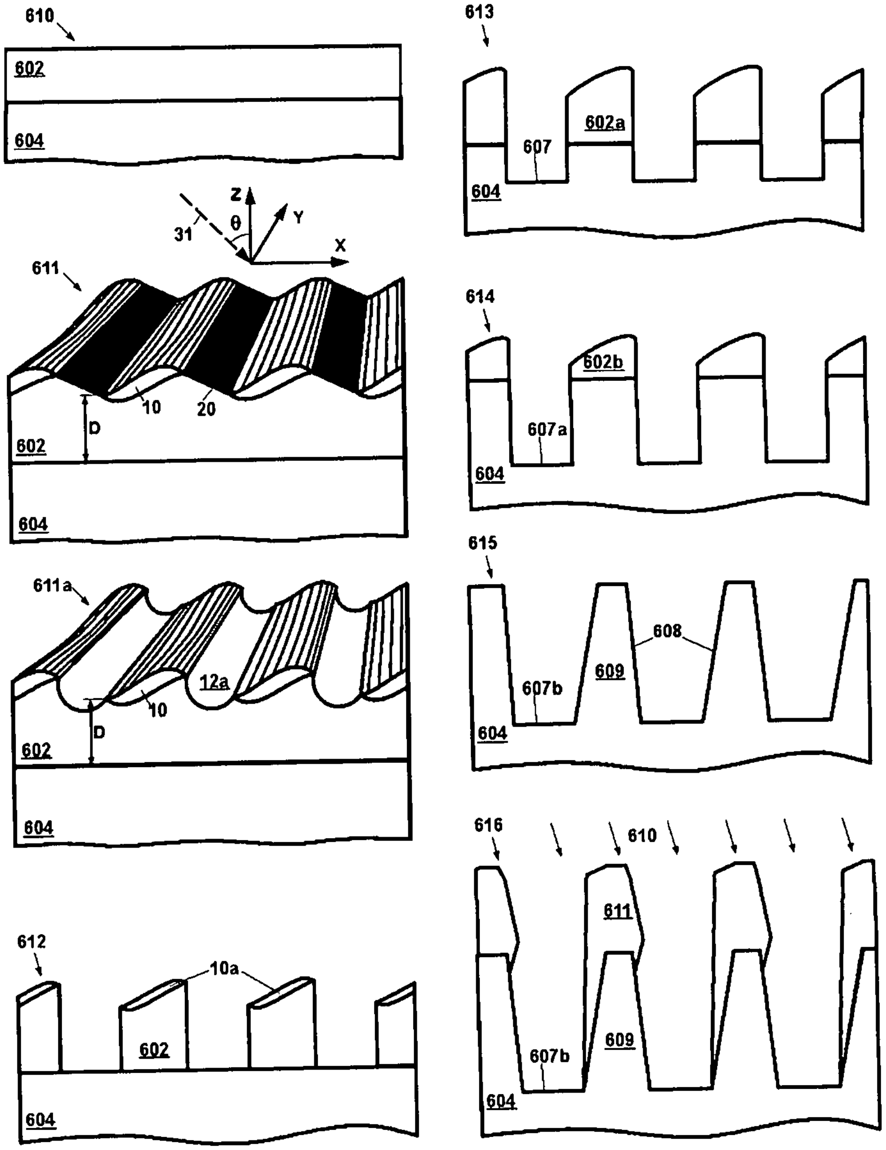

610
602
604
Z
θ
Y
31
X
611
10
20
D
602
604
611a
12a
10
D
602
604
612
10a
602
604
613
602a
607
604
614
602b
607a
604
615
608
609
607b
604
616
610
611
607b
609
604

FIG. 6

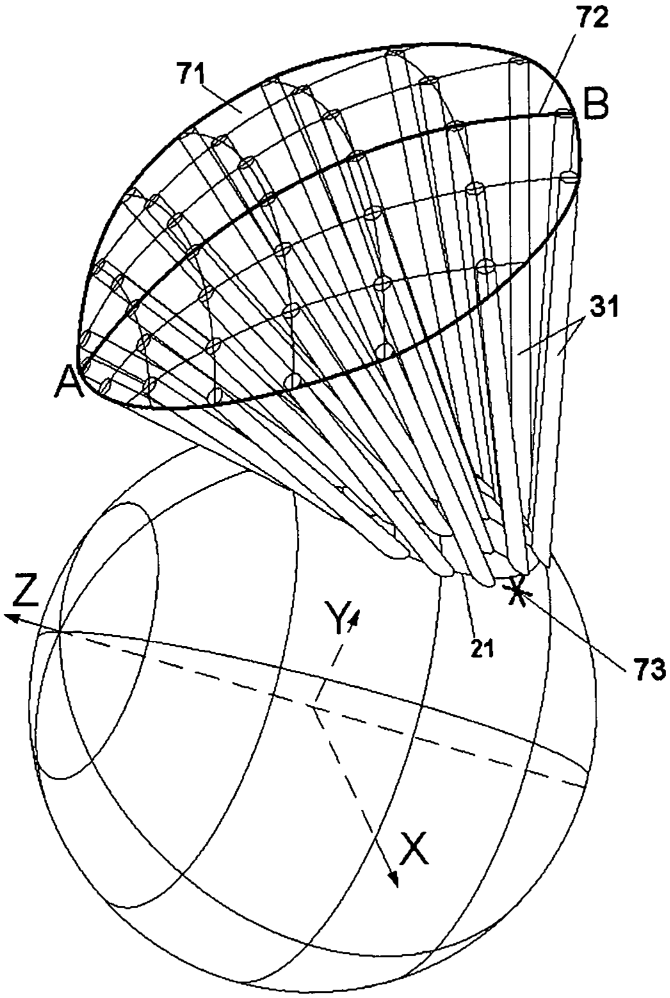


FIG. 7

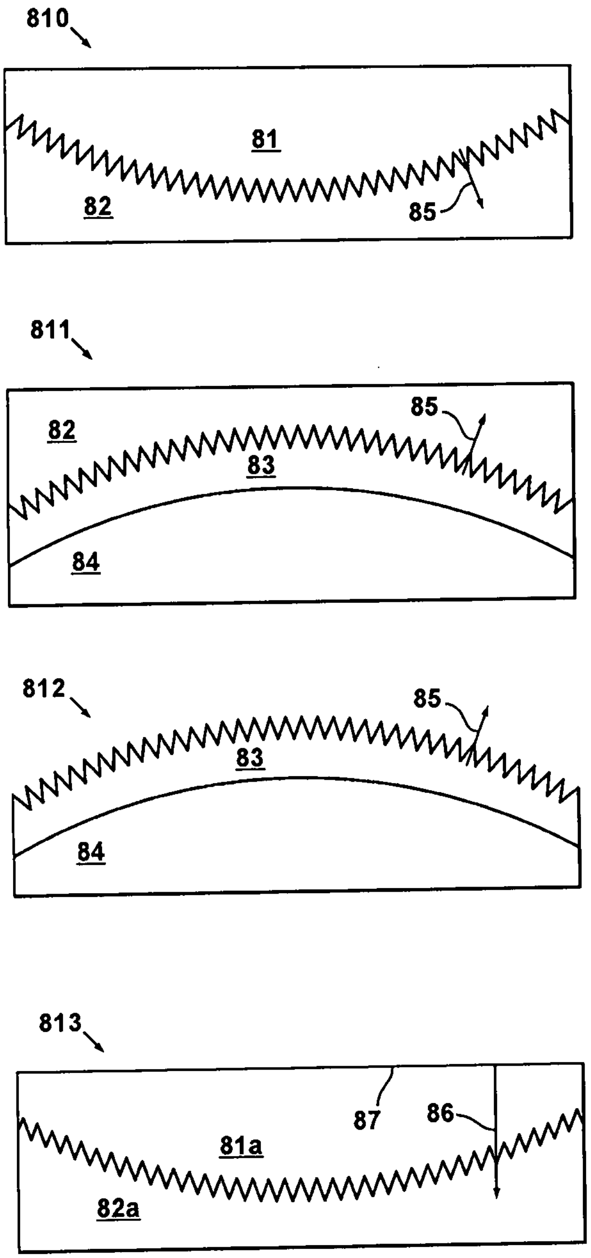


FIG. 8

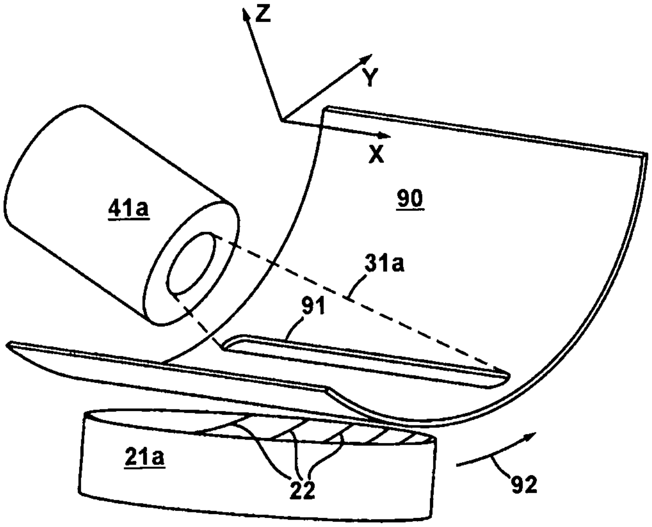


FIG. 9A

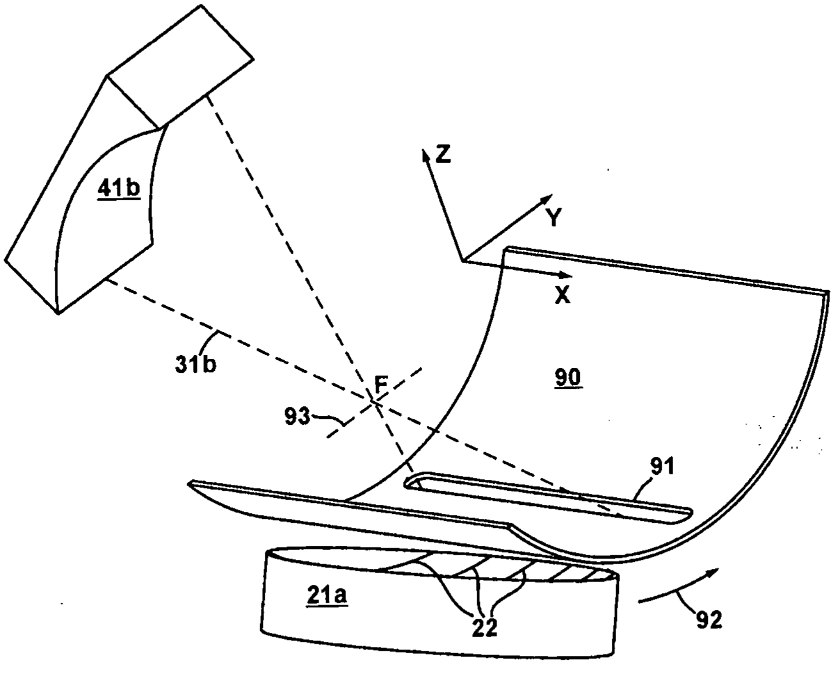


FIG. 9B

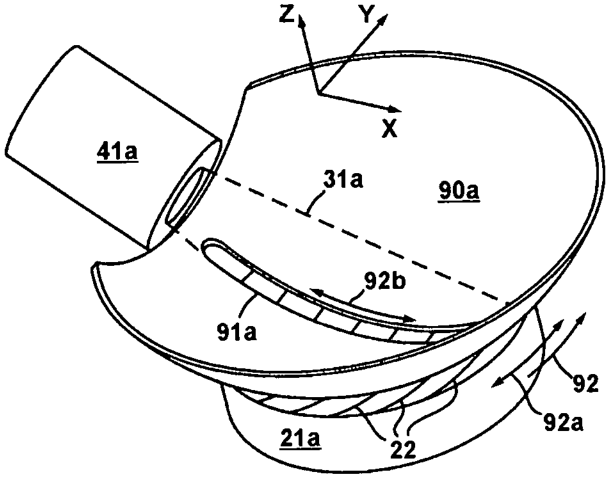

Z
Y
X
41a
31a
90a
92b
91a
92
92a
21a
22

FIG. 9C

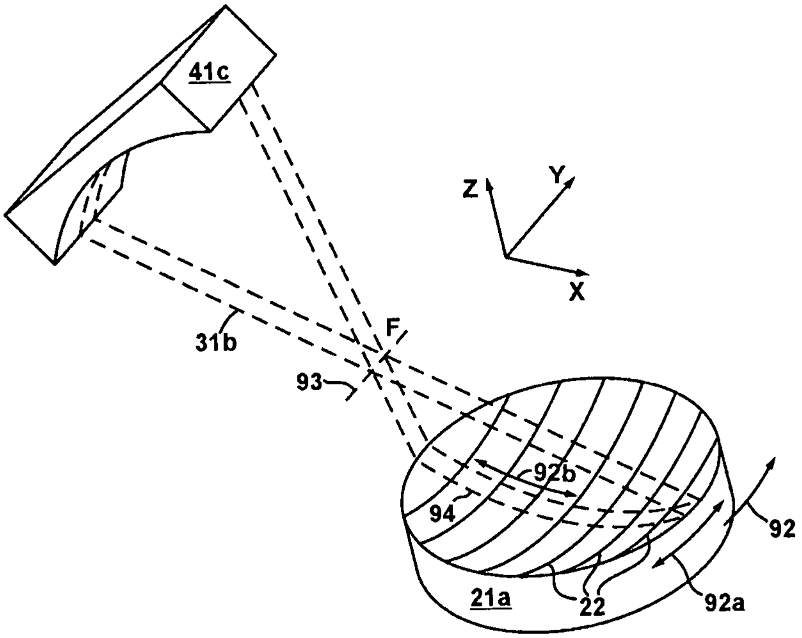

41c
Z
Y
X
31b
F
93
92b
94
92
92a
21a
22

FIG. 9D

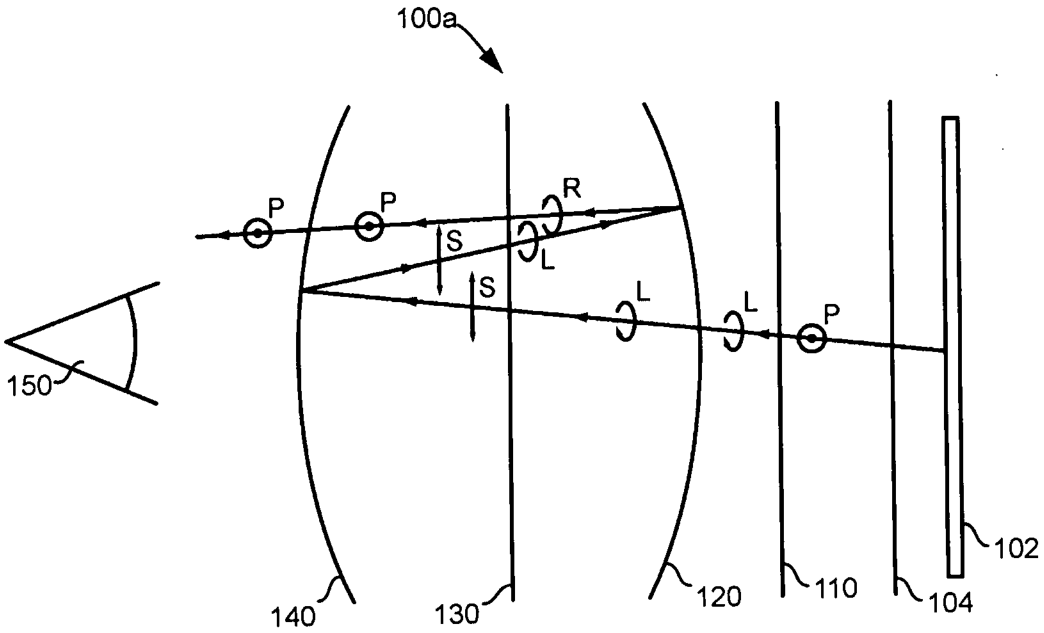


FIG. 10A

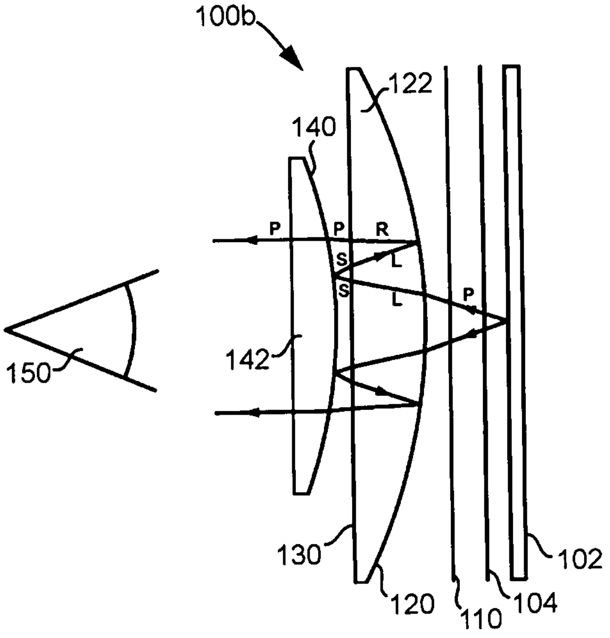


FIG. 10B

OPTICAL DEVICES WITH NANOWIRE GRID POLARIZER ON A CURVED SURFACE AND METHODS OF MAKING AND USING

FIELD

[0001] The invention relates to optical devices that contain a curved nanowire grid polarizer. The invention also relates to methods of making and using the optical devices.

BACKGROUND

[0002] Optical devices, such as virtual reality devices, display images from an image source. These devices often incorporate polarizers.

[0003] Wire grid polarizers are widely used in, for example, devices for graphic information imaging (e.g., see U.S. Pat. No. 6,452,724, incorporated herein by reference). The commonly-used technology for manufacturing these devices is based on optical or interference lithography. However, the cost associated with the use of the tools designed for these applications is considered very significant. The existing approach and tools make it difficult to fabricate wire grid polarizers on curved substrates such as spherical or other more complex optical shapes. In addition, the existing approach makes it is very difficult to create wire grid structures with a period of 150 nm or less. While different applications have different requirements, structures with smaller feature size are usually associated with higher performance.

BRIEF SUMMARY

[0004] A variety of optoelectronic and other applications can benefit from efficient methods for forming arrays of nanowires with a period of 150 nm or less on curved surfaces.

[0005] To manufacture such structures, a curved hard nanomask is formed by irradiating a curved layer of a first material with an ion flow. The curved hard nanomask may be used in transferring a substantially periodic pattern onto a curved substrate. This nanomask includes a substantially periodic array of substantially parallel elongated elements having a wavelike cross-section and oriented along the lines of intersections of the curved substrate surface with a set of parallel planes. At least some of the elements have the following cross-section: an inner region of first material, a first outer region of a second material covering a first portion of the inner region, and a second outer region of the second material covering a second portion of the inner region and connecting with the first outer region at a wave crest. The first outer region is substantially thicker than the second outer region. The second material is formed by modifying the first material using an ion flow. The substantially parallel, elongated elements having the wavelike cross-section are positioned on the curved layer of the first material along the lines of intersections of the curved layer surface with a set of parallel planes.

[0006] In at least some embodiments, the average period of the substantially periodic array is in a range from 20 to 150 nm.

[0007] In at least some other embodiments, the curved substrate is a lens having a diameter in a range of 4-200 mm.

[0008] Another embodiment is a method of forming a curved hard nanomask for transferring a substantially periodic pattern onto a curved substrate. The method includes depositing a first material to form a curved surface layer on top of a surface of a curved substrate; and irradiating the surface of the curved surface layer with a flow of ions until a curved hard nanomask is formed, the nanomask including a substantially periodic array of substantially parallel elongated elements having a wavelike cross-section and oriented along the lines of intersections of the layer surface with a set of parallel planes, at least some of the elements having the following structure in cross-section: an inner region of first material, a first outer region of a second material covering a first portion of the inner region, and a second outer region of the second material covering a second portion of the inner region and connecting with the first outer region at a wave crest, where the first outer region is substantially thicker than the second outer region, and where the second material is formed by modifying the first material by the ion flow, where the ion flow is arranged so as a local plane of ion incidence is substantially perpendicular to the set of parallel planes and oriented along a local surface normal of the surface layer.

[0009] In at least some embodiments, the curved substrate is a lens, during the formation of curved hard nanomask the lens is moved with respect to the ion flow, and the ion flow is shaped to have an ion beam with a size (D**1**) in the ion incidence plane which is determined by a radius of curvature (R) of the curved lens surface as D**1**≤R/6 or D**1**≤R/3.

[0010] In at least some embodiments, the first material is silicon and a layer of amorphous silicon containing 5-15 at % of Au is deposited on the surface of the curved layer of silicon prior to ion irradiation and the curved substrate is a lens. During the formation of the curved hard nanomask the lens is moved with respect to the ion flow, and the ion flow is shaped to have an ion beam with a size (D**1**) in the ion incidence plane which is determined by a radius of curvature (R) of the curved lens surface as D**1**≤R/2.

[0011] In at least some embodiments, the curved substrate is a lens. During the formation of the curved hard nanomask the lens is moved with respect to the ion flow, and the ion flow is shaped to have an ion beam with a size (D**2**) in the plane perpendicular to the ion incidence plane which is determined by a radius of curvature (R) of the curved lens surface as D**2**≤R/15.

[0012] In at least some other embodiments, the curved substrate is positioned stationary with respect to a specially arranged ion flow.

[0013] Another embodiment is an optical device that may include a first quarter wave plate; a half mirror; a second quarter wave plate, where the half mirror is disposed between the first and second quarter wave plates; and a curved nanowire grid polarizer, where the second quarter wave plated is disposed between the half mirror and the curved nanowire grid polarizer. The curved nanowire grid polarizer may include a curved substrate, a non-regular, substantially periodic array of substantially parallel, elongated nanoridges disposed on the curved substrate and having a wave-ordered structure and being oriented along a first direction, and an array of metal nanowires disposed on the array of nanoridges.

[0014] In at least some embodiments, the optical device further includes an image source, where the first quarter wave plate is disposed between the image source and the half mirror. In at least some embodiments, the optical device further includes a polarizer disposed between the image source and the first quarter wave plate. In at least some embodiments, a period of the substantially periodic array is in a range from 20 to 150 nm.

[0015] In at least some embodiments, the nanoridges are formed by pattern transfer from a curved hard nanomask including a substantially periodic array of substantially parallel elongated elements having a wavelike cross-section and oriented along the first direction wherein, at least some of the elements of the nanomask have the following structure in cross-section: an inner region of first material, a first outer region of a second material covering a first portion of the inner region, wherein the second material is formed by modifying the first material using an ion flow, where the substantially parallel, elongated elements having the wavelike cross-section are formed in a curved layer of the first material deposited on the curved substrate, wherein the first direction is along lines of intersections of a surface of the curved layer with a set of parallel planes and wherein a plane of incidence of the ion flow is substantially perpendicular to the first direction. In at least some embodiments, the pattern transfer includes transferring a pattern of the elongated elements on the nanomask to a surface of a curved mold and using the curved mold to form the array of nanoridges of the curved nanowire grid polarizer.

[0016] In at least some embodiments, the curved substrate and the substantially periodic array of substantially parallel, elongated nanoridges disposed on the curved substrate are made of optically transparent polymeric material. In at least some embodiments, the optical device is a virtual reality device. In at least some embodiments, the half mirror is curved. In at least some embodiments, the curved nanowire grid polarizer is convex relative to a viewer using the optical device. In at least some embodiments, the curved nanowire grid polarizer is concave relative to a viewer using the optical device. In at least some embodiments, the half mirror and the second quarter wave plate are disposed together on a lens.

[0017] Another embodiment is a method of making a curved nanowire grid polarizer for an optical device that includes depositing a first material to form a curved surface layer on top of a surface of a curved substrate; irradiating the surface of the curved surface layer with a flow of ions until a curved hard nanomask is formed, the nanomask including a substantially periodic array of substantially parallel elongated elements having a wavelike cross-section, at least some of the elements having the following structure in cross-section: an inner region of first material, a first outer region of a second material covering a first portion of the inner region, and a second outer region of the second material covering a second portion of the inner region and connecting with the first outer region at a wave crest, wherein the first outer region is substantially thicker than the second outer region, and wherein the second material is formed by modifying the first material by the flow of ions, wherein the elongated elements are oriented along lines of intersections of the curved surface layer with a set of parallel planes, and wherein the flow of ions is arranged so as a local plane of ion incidence is substantially perpendicular to the set of parallel planes and oriented along a local surface normal of the curved surface layer; transferring a pattern of the elongated elements of the nanomask to a surface of a curved, optically transparent substrate to form a non-regular, substantially periodic array of substantially parallel, elongated nanoridges; and disposing a metal layer on the nanoridges to form an array of metal nanowires of a curved nanowire grid polarizer.

[0018] In at least some embodiments, transferring a pattern includes transferring the pattern of the elongated elements on the nanomask to a surface of a curved mold and using the curved mold to form the array of nanoridges of the curved nanowire grid polarizer; and imprinting an optically transparent polymeric material using the curved

[0019] **[text missing or illegible when filed]**

[0020] FIG. **2**A is a perspective view of the arrangement of a curved hard nanomask on a convex spherical surface, according to the invention.

[0021] FIG. **2**B is a perspective view of the arrangement of a curved hard nanomask on a concave spherical surface, according to the invention.

[0022] FIG. **3** illustrates perspective views of a fixed ion beam and relative positions of a spherical segment during its movement under the ion beam, according to the invention.

[0023] FIG. **4** schematically illustrates an ion beam tool for forming a curved hard nanomask on a moving curved substrate, according to the invention.

[0024] FIG. **5** shows a SEM top view image of a curved WOS hard nanomask having a period of 80 nm and radius of curvature of R=60 mm formed on a moving substrate by two-step irradiation of an amorphous silicon layer with a N_2^+ fixed ion beam of about 5 mm in diameter having energy E=3.7 keV at an angle of bombardment θ_1=44° from surface normal at the first step and at θ_2=60° at the second step, according to the invention.

[0025] FIG. **6** schematically illustrates steps in one embodiment of a method for formation of a device, such as a wire grid polarizer, using a curved hard nanomask formed in an amorphous silicon layer, according to the invention.

[0026] FIG. **7** is a perspective view of a special grid surface of an ion source to manufacture a curved hard nanomask on a fixed curved substrate, according to the invention.

[0027] FIG. **8** shows cross-sectional views of polymeric structures with elongated nanoridges formed on curved surfaces formed using nanoimprint lithography, according to the invention.

[0028] FIG. **9**A illustrates a perspective view of a round ion source producing a divergent ion beam, which is shaped by a straight slit in a cylindrical screen, to irradiate a concave spherical substrate during its rotational movement under the slit, according to the invention.

[0029] FIG. **9**B illustrates a perspective view of a linear cylindrical ion source producing a convergent ion beam, which is shaped by a straight slit in a cylindrical screen, to irradiate a concave spherical substrate during its rotational movement under the slit, according to the invention.

[0030] FIG. **9**C illustrates a perspective view of a round ion source producing a divergent ion beam, which is shaped by a curved slit in a spherical screen, to irradiate a concave spherical substrate during its rotational movement under the slit, according to the invention.

[0031] FIG. **9**D illustrates a perspective view of a linear cylindrical ion source producing a convergent, flat ion beam which irradiates a linear stripe area across the surface of a concave spherical substrate during its rotational movement, according to the invention.

[0032] FIG. **10**A illustrates one embodiment of an optical device, such as a virtual reality device, according to the invention.

[0033] FIG. **10**B illustrates another embodiment of an optical device, such as a virtual reality device, according to the invention.

DETAILED DESCRIPTION

[0034] Detailed descriptions of the preferred embodiments are provided herein. It is to be understood, however, that the present inventions may be embodied in various forms. Therefore, specific implementations disclosed herein are not to be interpreted as limiting.

[0035] A method for nanorelief formation on a film surface, utilizing plasma modification of a wave-ordered structure (WOS) formed on amorphous silicon layer, was disclosed in Russian Patent Application RU 2204179, incorporated herein by reference.

[0036] An example of this approach is schematically illustrated on FIGS. **1**A, **1**B and **1**C. First, a layer of amorphous silicon **2** is deposited on top of the target thin film layer **4**. Then, the silicon layer is sputtered with a flow of nitrogen ions **31** to create a wave ordered nanostructure **1**. The resultant wave-ordered nanostructure has relatively thick regions of amorphous silicon nitride **10** and relatively thin regions of amorphous silicon nitride **20** situated respectively on the front and back sides of the waves in the wave-ordered structure **1**. The waves (elements) of the wave-ordered structure are oriented substantially in one direction along one axis. As shown, the wave troughs are spaced from the surface of the film layer **4** by a distance D that is usually less than the nanostructure period **3**. After the wave-ordered nanostructure **1** is formed, its planar pattern, which is shown in FIG. **1**A, is transferred into the underlying film layer **4** by selectively etching the amorphous silicon layer **2** while using regions **10** and **20** as a nanomask. The intermediate etched structure, which is shown in FIG. **1**C as an array of nanostructures **11**, is composed from amorphous silicon nanostripes **2** covered by the regions of amorphous silicon nitride **10**. The layer **4** may be etched in exposed areas **12** between silicon nanostripes **2**.

[0037] Ion beam techniques have been used to shape and polish curved optical surfaces through precise material removal by ion sputtering process, as disclosed in Michael Zeuner, Sven Kiontke, Ion Beam Figuring Technology in Optics Manufacturing: An established alternative for commercial applications, Optik & Photonik, Vol. 7, No. 2, 2012, pp. 56-58; and Vladimir Chutko, Ion Sources, Processes, Design Issues: Ion beam figuring, Control Parameters, Vacuum Technology & Coating Magazine, September 2013, pp. 2-10, both of which are incorporated herein by reference. However, these ion beam tools cannot be used directly to form wave-ordered structures on curved surfaces such as, for example, spherical surfaces, with orientation of waves along the latitude lines (parallel lines) on the globe, for fabricating a linear polarizer.

[0038] FIG. **2**A is a perspective view of a curved hard nanomask on a convex spherical surface. In at least some embodiments, the polarizer substrate is a transparent, spherical segment **21** having a diameter **25**, i.e. the diameter of the segment base. The diameter **25** may be in a range of, for example, 4-200 mm. A thin layer of amorphous silicon (a-Si) is deposited onto the spherical segment **21**. The elongated elements of a WOS nanomask are positioned along parallel lines **22** (circle arcs), which are lines of intersections of the curved layer surface with a set of parallel planes **23** that, in the illustrated embodiment, are parallel to the YZ plane of a Cartesian coordinate system XYZ. The origin of the coordinate system is positioned at the top of the spherical segment **21**.

[0039] In at least some other embodiments, the transparent polarizer substrate **21***a* has a concave spherical surface, as shown in FIG. **2**B. On the concave substrate **21***a* the elements of the WOS nanomask are positioned along parallel lines **22** (circle arcs), which are lines of intersections of the curved a-Si layer surface with a set of parallel planes **23** that, in the illustrated embodiment, are parallel to the YZ plane of a Cartesian coordinate system XYZ. The origin of the coordinate system is positioned at the lowermost point of concave surface of the substrate **21***a*.

[0040] In at least some embodiments, uniform (in terms of density and height) and parallel alignment of the nanomask elements on a spherical surface is achieved through the movement of the substrate under a fixed ion beam as shown in FIG. **3**. In **301**, the ion beam **31** irradiates the near central area of spherical segment **21**. The segment **21** is a part of the sphere. The segment **21** moves under the ion beam along parallel lines **22**. In **302**, the beam is positioned near the periphery of the segment **21**. This segment motion is due to the rotation of the sphere around the Z axis by, for example, an angle β=20°. In at least some embodiments, the segment **21** moves continuously along the lines **22** with a velocity of about 140 μm/s to form one linear stripe of nanomask elements and stops. Then segment **21** makes a step of, for example, about 1 mm for about 0.1 seconds along the line **24** to form the next linear stripe of the nanomask elements along the lines **22** in the opposite direction and so on. This forms a meander scanning pattern **26** which is labeled **302***a*. The position of the spherical segment **21** in **303** is rotated around Y axis by, for example, an angle γ=20° with respect to the position in **302**. In at least some embodiments, the speed of segment movement along lines **22** depends on the ion beam current and the larger the beam current the greater is the speed. For example, the speed of 140 μm/s may correspond to the beam current of about 30 μA and the speed of 4.7 mm/s may correspond to the beam current of about 1 mA. The step movement in the direction along the lines **24** may be, for example, in the range from 0.02 to 0.1 of the ion beam diameter and the smaller the step the faster should be the speed along the lines **22** to keep the ion fluence constant. In some embodiments, the irradiation is implemented using a divergent ion beam with an ion beam incidence angle with respect to the local surface normal of spherical segment that is in the range θ=49°-55°.

[0041] In some embodiments with divergent ion beams, another sequence of substrate motion in a meander scanning pattern is implemented. This meander scanning pattern **26***a* is labeled **302***b* in FIG. **3**. A spherical substrate **21** is moved along lines **24**, which are meridians of the globe, and after each line **24** is completed a step along lines **22** is implemented at the periphery of the substrate **21**. Ion fluence (dose) is uniformly distributed over the substrate surface at equal local angles of ion incidence. The elements of the WOS nanomask are self-aligned perpendicular to the local ion incidence plane and, in particular for the example illustrated in FIG. **3**, the elements of the WOS nanomask are positioned along the lines **22**, i.e. along the parallels of the globe.

[0042] In at least some embodiments, in the scanning system of FIG. **3**, the ion beam may not have a cylindrical shape and may be more extended along meridian lines **24** with a size D**1** in the ion incidence plane to cover the range of ion incidence angles from, for example, 44° to 60° and may be narrowed along parallel lines **22** having the size D**2** to limit deviation of WOS nanomask elements from the parallel lines **22**.

[0043] In some embodiments, substrate motion under a fixed ion beam is carried out in a repetitive manner with the ion fluence subdivided between multiple repetitive meander scans **26** or **26***a*. In this case, the uniformity of ion fluence over the substrate surface may be less dependent on the ion current stability and the greater the number of scans the more uniform is the ion fluence.

[0044] In some embodiments, substrate scanning is implemented with a variable, position-dependent speed along lines **22** and **24** of FIG. **3** to compensate for spherical distortions of the rectangular meander patterns **26** and **26***a* and to obtain uniform ion fluence distribution over the surface of the spherical substrate **21**. For example, the lines **22** are arcs with different radii and the radius decreases from the segment center to its periphery. In the meander pattern **26**, the arcs are along the lines **22** and constant angular speed for all lines results in smaller fluence at the segment center and larger fluence at peripheral lines **22**. To compensate for this fluence nonuniformity the segment **21** can be moved at greater angular speed along peripheral lines **22** in, for example, reverse proportion to the arc radius.

[0045] The formation of a curved WOS nanomask was implemented in an ion beam system, which is schematically illustrated in FIG. **4**. The system includes a vacuum chamber **42**, a pump system **43**, and a gridded ion source **41**, which forms the ion beam **31**. A moving mechanism **45** enables rotation of the spherical segment **21** around the Z axis and the Y axis. Elements of a curved WOS nanomask are aligned substantially parallel along the lines **22**.

[0046] On the spherical surface, the larger the beam size (D**2**) in the plane perpendicular to the ion incidence plane, the greater is the deviation of the WOS nanomask elements from the lines **22** of FIG. **3** at both of the most distant, opposite beam edges crossing line **22**. To decrease such a deviation and to enhance the alignment of the WOS nanomask elements substantially parallel to the lines **22**, in some embodiments, during the formation of the curved WOS nanomask, the spherical substrate is moved with respect to an ion beam having a size D**2** which is determined by the radius of substrate curvature (R) as $D2 \le R/15$.

[0047] In some embodiments, the spherical segment is a lens having a radius R of the curvature of the external surface. The collimated ion beam, depending on its diameter, has different angles of ion incidence θ across the beam on the curved surface. In some embodiments, the variation of θ in the ion incidence plane may be within the range $\theta=44°$-60° and the ion beam size D1 in the ion incidence plane is limited to $D1 \le R/6$. Taking into account the ion dose dependence of the WOS formation process, this ion beam size restriction may be relaxed. In at least some embodiments, the ion beam size D**1** is limited by the surface curvature radius R to $D1 \le R/3$.

[0048] In some embodiments, to accelerate the WOS formation process, a gold-containing film is deposited onto the amorphous silicon layer prior to ion irradiation. In some embodiments, the gold-containing film has a thickness in the range of 10 to 25 nm. It has been found that a gold-containing film deposited onto a silicon surface may greatly reduce the time of WOS formation process under nitrogen ion bombardment. Au^+ ions implanted into monocrystalline silicon at the energy of 12 keV and fluence 1016 cm^{-2} accelerated the WOS formation process by about a factor of two for N_2^+ ions with $E=8$ keV and an angle of ion incidence of $\theta=45°$. It is noteworthy that Au implantation did not result in any topographical roughness. Thus, the presence of gold in a surface silicon layer can result in the acceleration of WOS formation. It was also found that the acceleration effect is often angular dependent and may be greater for N_2^+ ion incidence angles of $\theta=41°$-43° whereas almost no acceleration is observed for $\theta=55°$-60°. The nature of angular dependence of WOS formation acceleration may make WOS formation depth almost independent for θ in the range of $\theta=41°$-60°, which means that the ion beam size restriction in scanning system may be further relaxed. In at least some embodiments, on the basis of these observations the ion beam size D1 in the ion incidence plane is related to the substrate surface curvature radius R by $D1 \le R/2$.

[0049] In some embodiments, a composite Si—Au layer, 10-40 nm thick, with Au content ranging from 5-15 at % is deposited on the surface of an amorphous (a-Si) layer prior to N_2^+ ion irradiation. The Si—Au layer may be deposited, for example, by magnetron sputtering using a two-component Si/Au target, in which the silicon wafer is used as a mask with through holes leading to a closely attached Au wafer. For this two-component target with masked Au surface the Au content in the deposited Si—Au film is related to the amount of exposed gold area and by sputtering rates of Au and Si in the particular magnetron sputtering system.

[0050] In some embodiments, depending on beam focusing, the substrate (lens) diameter **25** shown in FIG. **2**A may be in the range 4 to 200 mm.

[0051] FIG. **5** shows a SEM top view image of a curved WOS hard nanomask having a period of 80 nm formed by two-step irradiation of an amorphous silicon layer with N_2^+ ions having energy $E=3.7$ keV at an angle of bombardment $\theta_1=44°$ from surface normal at the first step and at $\theta_2=60°$ at the second step. During the irradiation, the curved substrate was moved under a fixed ion beam having a diameter of about 5 mm. The substrate curvature radius was $R=60$ mm.

[0052] FIG. **6** illustrates one embodiment of a method to manufacture a curved wire grid polarizer or other device on a transparent quartz spherical substrate. It shows a structure **610**, including a substrate (e.g., quartz) **604** and a layer of amorphous silicon **602** (for example, approximately 200-400 nm thick).

[0053] The amorphous silicon layer **602** may be deposited onto the curved substrate surface, for example, by magnetron sputtering of a silicon target, by silicon target evaporation with an electron beam in high vacuum, or by any other method known in art. The thickness of the layer **602** is selected to enable the formation of a nanostructure with desired period, λ, (for example, a period of approximately 70-90 nm).

[0054] A curved WOS is formed on the surface of substrate **604**, which results in the structure **611**. In this example, the curved WOS is formed using an oblique ion beam **31** of nitrogen N_2^+ ions positioned at the local ion incidence plane XZ (the plane which is defined by a local normal to the surface of the material and a vector oriented in the direction of the ion flow) at angle θ to the surface normal (Z-axis). In this particular example, to reduce the number of intersections of WOS nanomask elements (waves), the nitrogen ion bombardment is implemented in two steps with different bombardment angles θ. At the first step θ=44° and at the second step θ=60°. The ion energy for both steps is approximately equal to 3.7 keV. The ion fluence for the first step is approximately ten times greater than that for the second step. The resultant WOS nanomask having a period of 80 nm is shown in FIG. **5**. The thick silicon nitride regions **10** and thin silicon nitride regions **20** on the opposite slopes of the waves are mostly elongated in the Y-axis direction. As shown in the structure **611**, the wave troughs are spaced from the quartz substrate surface **604** by a distance D, which in a given particular example was of about 60 nm.

[0055] Depending on the chosen thickness of the modified layer **20** on the back side of waves of the wavelike nanostructure, a preliminary breakthrough etching step might be performed using argon ion sputtering or sputtering by ions of etching plasma for a relatively short period of time to remove the modified layer **20** from the back side. To remove regions **20** one can also perform wet etching in HNO_3—HF solution for a short period of time.

[0056] In at least some embodiments, the structure **611** may be optionally wet-etched to form the structure **611*a*** having nanotrenches **12*a*** in place of regions **20**. This optional wet etching may improve further etching steps in plasma.

[0057] The curved WOS and nanostructures formed from the curved WOS by etching with the use of regions **10** and **20** as a nanomask can be characterized as a quasi-periodic, anisotropic array of elongated ridge elements having a WOS pattern, each ridge element having a wavelike cross-section and oriented substantially in one direction (Y-axis). An example of the pattern of a WOS is shown in FIG. **1**A, and an example of the pattern of a curved WOS is shown in FIG. **5**. Ridge elements may be waves or other features having tilted tops or sidewalls. In the wave nanostructure **1** of FIG. **1**B, the ridge elements are waves with regions **10** and **20** on opposite wave slopes. In the nanostructure **11** of FIG. **1**C, the ridge elements are stripes covered by tilted regions **10** and spaced by trenches **12**. One can see that the ridge elements are elongated and mostly oriented in the direction of the Y-axis as shown in FIGS. **1**A and **5**.

[0058] Referring again to FIG. **6**, the structures **611** or **611*a*** can be modified by applying a reactive-ion plasma (Cl_2, Cl_2—Ar, HBr—O_2 or Cl_2—He—O_2 or by any other method known in art) to the amorphous silicon layer **602**, using the curved nanomask having regions **10** of silicon nitride. In at least some embodiments, the process results in a modified nanomask having silicon nitride regions **10*a*** formed on top of stripes of amorphous silicon **602**, as shown in the structure **612** of FIG. **6**. The thickness of regions **10*a*** may become thinner than the thickness of original regions **10** during plasma etching.

[0059] In the next step, anisotropic etching is applied to the substrate **604**. Depending on the type of the substrate material, different types of plasma can be used (for example, for a quartz substrate, CF_4—H_2, CHF_3, C_4F_6—Ar or C_4F_8—Ar based plasma can be used). The resulting structures **613-615** may include trenches **607**, **607*a***, and **607*b***. During etching the amorphous silicon stripes **602** may be modified by plasma to the structures **602*a*** and **602*b*** or may be fully etched, which may result in tilted sidewalls **608** of quartz nanoridges **609**. In some embodiments, the structure **612** is modified by ion sputtering using a N_2^+ ion beam directed along the ridge elements **602** in the YZ ion incidence plane at an angle of, for example, about 53° to the Z axis. The resultant quartz nanoridges have a sawtooth triangular profile with sharp bottoms and tops as shown in FIG. **8**. The pattern of nanoridges arising from the etching processes is transferred from the curved WOS hard nanomask.

[0060] Oblique deposition of aluminum can be performed on the array of quartz nanoridges as shown in the structure **616** to produce a curved wire-grid polarizer. For uniform deposition, the curved substrate may be moved under the flow of metal atoms **610**. In some embodiments, special masks may be applied across the flow of metal atoms to obtain a uniform (in terms of density and height) array of metal nanowires **611** disposed over the nanoridges **609**. The array of metal nanowires is substantially periodic, but is also non-regular in that the nanowires are not arranged in a regular array of nanowires. In some embodiments, the mask may include a slit. During the aluminum deposition, the slit mask is positioned along the quartz nanoridges, and the quartz substrate is rotated under the mask in a direction perpendicular to the mask extension for uniform aluminum deposition to the nanoridges.

[0061] In at least some embodiments, a curved hard WOS nanomask may be manufactured on fixed spherical substrates by a gridded ion source having a special grid surface, which is shown in FIG. **7**. The grid **71** provides microbeams **31** that irradiate the surface of the spherical segment **21** with the same local incidence angle (for example, in the range θ=49°-55°). The surface of grid **71** may be constructed from an arc circle AB **72** having a center **73** (the quasi focus of the microbeams in ZY plane). The surface of the grid **71** may be produced through the rotation of the arc **72** around the Z axis thus forming the surface of revolution to which each microbeam is normal. The border of the surface of the grid **71** is determined by the microbeams positioned at the border of the spherical segment. In at least some embodiments, the grid **71** may be used to shape the ion flow for manufacturing the curved WOS nanomasks on fixed spherical substrates. In at least some embodiments, the complex grid shape is approximated by a spherical shape.

[0062] In at least some embodiments, the spherical surface of a quartz substrate with quartz nanoridges may be used as a master mold to transfer a nanoridge pattern to the surface of a curved polymeric substrate. It will be recognized that materials other than quartz can also be used for the substrate and nanoridges. In at least some embodiments, the spherical surface of a silicon substrate with silicon nanoridges may be used as a master mold to transfer a nanoridge pattern to the surface of a curved polymeric substrate. In some embodiments, the master mold has a convex surface. In some other embodiments, the master mold has a concave surface. In some embodiments, the nanoridge pattern of the silicon master mold is transferred into the surface of a nickel thin layer using, for example, nickel electroless plating onto the silicon mold surface and then a thick nickel layer is electrodeposited to make a nickel mold.

[0063] In structure **810** of FIG. **8** the quartz master mold **81** with nanoridges on its surface is used to transfer the nanoridge pattern into the surface of an intermediate hard polymeric mold **82** of, for example, polycarbonate. In structure **811** of FIG. **8**, the intermediate hard polymeric mold **82** is applied to the UV curable surface layer **83** on the surface of the polymeric substrate **84** during the process of soft nanoimprint lithography as known in the art. In structure **812** of FIG. **8**, the resultant nanoridge pattern is formed on the surface layer **83**, which is positioned on the polymeric substrate **84**. In structure **812** the sidewalls of each nanoridge may be positioned symmetrically with respect to the local surface normal **85**. In structure **813** of FIG. **8**, the sidewalls of each nanoridge on the surface of master mold **81***a* may be positioned symmetrically with respect to the normal **86** to the mold base **87**. This symmetrical nanoridge orientation allows the printing of higher nanoridges into the surface of a replica **82***a* compared to the oblique nanoridges in the structures **810**, **811**, and **812** of FIG. **8**. The oblique deposition of metal onto the polymeric nanoridges results in a curved wire-grid polarizer.

[0064] In at least some embodiments, the formation of a WOS nanomask on a concave substrate is carried out by linear ion flow to irradiate a linear stripe area on the substrate surface. FIG. **9**A shows one arrangement with a round ion source **41***a* generating a divergent ion beam **31***a*, which is directed to a straight slit **91** in a cylindrical screen **90**. The ion source **41***a* may be, for example, a gridded ion source. The divergent ion beam **31***a* irradiates a concave substrate **21***a* through the slit **91** thus irradiating a linear stripe area on the substrate surface. To irradiate the surface of the substrate **21***a*, the substrate is rotationally moved around the X axis under the slit **91** in the direction **92**. The slit **91** is extended along the X axis and the ion incidence plane coincides with the XZ plane. The parallel lines **22**, along which the elements of WOS nanomask are oriented, are perpendicular to the ion incidence plane during ion bombardment and rotational motion of the substrate **21***a* under the slit **91**. The axis of cylinder screen **90** coincides with the X axis and the center of surface curvature of the substrate **21***a* is at the origin of the XYZ Cartesian coordinate system. The oblique position of the divergent ion beam **31***a* with respect to the concave substrate **21***a* and to the slit **91** provides approximately equal local angles of ion incidence along the irradiated linear stripe area of the substrate surface.

[0065] In comparison with the arrangement shown in FIG. **4** where the substrate is rotated around two axes, during ion irradiation in the arrangements shown in FIGS. **9**A-**9**D the substrate is rotated only around the X axis and the substrate motion system is simplified.

[0066] The arrangement shown in FIG. **9**B differs from that shown in FIG. **9**A in that the ion source **41***b* is a linear cylindrical ion source generating a convergent ion beam **31***b* having a crossover at focal line **93**, which is parallel to the Y axis. The ion source **41***b* may be, for example, a gridded ion source with a cylindrical grid.

[0067] In the arrangement shown in FIG. **9**C a curved slit **91***a* in a spherical screen **90***a* is used in place of the straight slit **91** in the cylindrical screen **90** shown in FIGS. **9**A and **9**B. In FIG. **9**C the centers of surface curvature of the spherical screen **90***a* and the concave substrate **21***a* coincide and are located at the origin of the XYZ Cartesian coordinate system. The curved slit **91***a* extends along the ZX plane thus forming the ion flow in the same ion incidence plane. The arrangement shown in FIG. **9**C may provide more uniform irradiation of the substrate because the distance between the substrate **21***a* and the curved slit **91***a* is constant whereas that distance varies in the case of the straight slit **91** of FIGS. **9**A and **9**B. However, the straight slit in a cylindrical screen is simpler to manufacture.

[0068] In the arrangement shown in FIG. **9**D the irradiation of the linear stripe area **94** on the surface of the substrate **21***a* is provided directly by a convergent ion beam **31***b* generated by a cylindrical ion source **41***c*. The ion beam **31***b* has crossover at focal line **93**, which is parallel to the Y axis. In at least some embodiments, the uniform fluence on the substrate surface is provided through the appropriate variation of ion beam intensity across the ion source or through slit width variation in the screens **90** and **90***a*.

[0069] In at least some embodiments, in the arrangements shown in FIGS. **9**C and **9**D, during ion irradiation the substrate **21***a* is rotationally moved in two directions, first direction **92***a* around the X axis and second direction **92***b* around the Y axis, to provide uniform ion fluence on the substrate surface. The substrate motion may be one or multiple meander scans.

[0070] The curved nanowire grid polarizers formed with the pattern transfer from the WOS nanomask, as described herein (for example, as described with respect to the embodiments illustrated in FIG. **8**), can be used in a variety of optical devices. These curved nanowire grid polarizers have a non-regular, substantially periodic array of substantially parallel, elongated nanoridges disposed on the curved substrate and having a wave-ordered structure and being oriented along a first direction. A metal layer is disposed on the nanoridges to form an array of nanowires.

[0071] FIG. **10**A illustrates one example of an optical device **100***a*. This optical device **100***a* can be, for example, a virtual reality device. The optical device **100***s* includes an image source **102**, an initial polarizer **104**, a first quarter wave plate **110**, a half mirror **120**, a second quarter wave plate **130**, and a curved nanowire grid polarizer **140** formed using pattern transfer from the curved WOS nanomask. Any of the methods and WOS nanomasks described above can be used to make the curved nanowire grid polarizer. For example, oblique deposition of metal onto the polymeric nanoridges formed using any of the curved WOS nanomask described above can result in the curved nanowire grid polarizer.

[0072] In the illustrated embodiment of FIG. **10**A, the half mirror **120** is curved. Using a curved half mirror **120** with a curvature in the opposite direction as the curved nanowire grid polarizer **140** can result in a shorter focal length of the optical arrangement making a more compact device. The curvatures of the half mirror **120** and the curved nanowire grid polarizer **140** can be determined to achieve desired device parameters. Such a determination can be made by experimentation, modeling, or any other suitable technique or any combination thereof. One example of device parameters is a diagonal field-of-view of 100 degrees, an exit pupil of 12 mm, an eye relief (distance from the eye cornea to the nearest optical surface) of 20 mm, diagonal size of the image source of 40 mm, a half mirror diameter of 60 mm, and a focal distance (from the image source **102** to the curved nanowire grid polarizer **140**) of 17 mm. These is one example of suitable parameters, but other sets of parameters can be used.

[0073] In at least one embodiment, light from an image source **102** passes through an initial polarizer **104** to provide linearly polarized light having P-polarization (perpendicular to the drawing sheet). Any suitable image source **102** can be provided including, but not limited to, LED, LCD, or OLED devices. Any suitable polarizer **104**, including, but not limited to, reflective or absorptive polarizers, may be used to initially polarize the light. Optionally, arrangements that recycle any light reflected by the initial polarizer **104** may also be used.

[0074] As illustrated in FIG. **10**A, the P-polarized light passes through the first quarter wave plate **110** and becomes left circularly polarized. Transmission through the half mirror **120** retains the light polarization. Passing through the second quarter wave plate **130** transforms the left circularly polarized light into linear polarized light having S-polarization (parallel to the drawing sheet). This S-polarized light reflects from the curved nanowire grid polarizer **140** back to the second quarter wave plate **130** which then changes the polarization into left circularly polarized. Next reflection from the half mirror **120** transforms the left circular polarization to right circular polarization and after transmission again through the second quarter wave plate **130** the light returns to the initial P-polarization and goes through the curved nanowire grid polarizer **140** to the viewer's eye **150**.

[0075] Any suitable quarter wave plates **110**, **130** can be used. Preferably, the half mirror **120** has approximately 50% reflection and 50% transmission which reduces the light transmission to the viewer to no more than 25% of the original intensity due to two interactions of the light with the half mirror. Naturally, the curved nanowire grid polarizer **140** will further reduce the intensity of light. The curved nanowire grid polarizer **140** formed from the WOS nanomask, as described herein, is highly reflective (particularly when compared to conventional linear reflective polarizers) and, at least in some embodiments, will produce a light transmission of up to 20% or more of the original intensity. In some embodiments, the curved nanowire grid polarizer **140** is convex relative to the viewer's eye **150***m* as shown in FIG. **10**A. In other embodiments, the curved nanowire grid polarizer **140** is convex relative to the image source as shown in FIG. **10**B.

[0076] FIG. **10**B illustrates another example of an optical device **100***b*. It differs from the device **100***a* shown in FIG. **10**A in that it includes lenses **122**, **142**, a half mirror **120** is disposed on the surface of the lens **122**, and a curved nanowire grid polarizer **140** that is convex toward the image source **102** and disposed on the surface of the lens **142**. The polarization states of the light are the same as in FIG. **10**A. The combination of reflective and refractive components makes it possible to compensate for spherical aberrations. However, in some embodiments aspherical lenses and mirrors may be used. In at least some embodiments, it is preferable to make lenses from polymeric optical transparent materials. Such polymeric lenses may be used as substrates for curved nanowire grid polarizers.

[0077] The high reflectivity (relative to conventional linear reflective polarizers) of nanowire grid polarizer **140** formed from the WOS nanomask, as described herein, can reduce the unwanted reflections in optical device which can produce higher image contrast.

[0078] In addition, the curved surface of the nanowire grid polarizer **140** can considerably widen the field of view for the optical device when compared to flat polarizers.

What is claimed as new and desired to be protected is:

1. An optical device, comprising:
a first quarter wave plate;
a half mirror;
a second quarter wave plate, wherein the half mirror is disposed between the first and second quarter wave plates; and
a curved nanowire grid polarizer, wherein the second quarter wave plated is disposed between the half mirror and the curved nanowire grid polarizer, the curved nanowire grid polarizer comprising:
a curved substrate,
a non-regular, substantially periodic array of substantially parallel, elongated nanoridges disposed on the curved substrate and having a wave-ordered structure and being oriented along a first direction, and
an array of metal nanowires disposed on the array of nanoridges

2. The optical device of claim **1**, further comprising an image source, wherein the first quarter wave plate is disposed between the image source and the half mirror.

3. The optical device of claim **2**, further comprising a polarizer disposed between the image source and the first quarter wave plate.

4. The optical device of claim **1**, wherein a period of the substantially periodic array is in a range from 20 to 150 nm.

5. The optical device of claim **1**, wherein the nanoridges are formed by pattern transfer from a curved hard nanomask comprising a substantially periodic array of substantially parallel elongated elements having a wavelike cross-section and oriented along the first direction wherein, at least some of the elements of the nanomask have the following structure in cross-section:
an inner region of first material,
a first outer region of a second material covering a first portion of the inner region, wherein the second material is formed by modifying the first material using an ion flow,
wherein the substantially parallel, elongated elements having the wavelike cross-section are formed in a curved layer of the first material deposited on the curved substrate, wherein the first direction is along lines of intersections of a surface of the curved layer with a set of parallel planes and wherein a plane of incidence of the ion flow is substantially perpendicular to the first direction.

6. The optical device of claim **5**, wherein the pattern transfer comprises transferring a pattern of the elongated elements on the nanomask to a surface of a curved mold and using the curved mold to form the array of nanoridges of the curved nanowire grid polarizer.

7. The optical device of claim **1**, wherein the curved substrate and the substantially periodic array of substantially parallel, elongated nanoridges disposed on the curved substrate are made of optically transparent polymeric material.

8. The optical device of claim **1**, wherein the optical device is a virtual reality device.

9. The optical device of claim **1**, wherein the half mirror is curved.

10. The optical device of claim **1**, wherein the curved nanowire grid polarizer is convex relative to a viewer using the optical device.

11. The optical device of claim **1**, wherein the curved nanowire grid polarizer is concave relative to a viewer using the optical device.

12. The optical device of claim **1**, wherein the half mirror and the second quarter wave plate are disposed together on a lens.

13. A method of making a curved nanowire grid polarizer for an optical device, the method comprising:

depositing a first material to form a curved surface layer on top of a surface of a curved substrate;

irradiating the surface of the curved surface layer with a flow of ions until a curved hard nanomask is formed, the nanomask comprising a substantially periodic array of substantially parallel elongated elements having a wavelike cross-section, at least some of the elements having the following structure in cross-section: an inner region of first material, a first outer region of a second material covering a first portion of the inner region, and a second outer region of the second material covering a second portion of the inner region and connecting with the first outer region at a wave crest, wherein the first outer region is substantially thicker than the second outer region, and wherein the second material is formed by modifying the first material by the flow of ions, wherein the elongated elements are oriented along lines of intersections of the curved surface layer with a set of parallel planes, and wherein the flow of ions is arranged so as a local plane of ion incidence is substantially perpendicular to the set of parallel planes and oriented along a local surface normal of the curved surface layer;

transferring a pattern of the elongated elements of the nanomask to a surface of a curved, optically transparent substrate to form a non-regular, substantially periodic array of substantially parallel, elongated nanoridges; and

disposing a metal layer on the nanoridges to form an array of metal nanowires of a curved nanowire grid polarizer.

14. The method of claim **13**, wherein transferring a pattern comprises transferring the pattern of the elongated elements on the nanomask to a surface of a curved mold and using the curved mold to form the array of nanoridges of the curved nanowire grid polarizer; and

imprinting an optically transparent polymeric material using the curved mold to form the non-regular, substantially periodic array of substantially parallel, elongated nanoridges.

15. The method of claim **13**, wherein the first material is silicon, amorphous silicon, silicon containing 5-15 at % of gold, silicon oxide, gallium arsenide, epitaxial gallium arsenide, gallium aluminum arsenide, epitaxial gallium aluminum arsenide, germanium, or silicon-germanium.

16. The method of claim **13**, wherein a thickness of the first outer region is at least 2 nm.

17. The method of claim **13**, wherein the elongated elements of the nanomask further comprise a second outer region of the second material covering a second portion of the inner region connected to the first outer region at a wave crest, wherein the first outer region is substantially thicker than the second outer region.

18. The method of claim **17**, wherein a thickness of the second outer region is no more than 1.5 nm.

19. The method of claim **13**, wherein the second material is silicon nitride, silicon nitride containing 5-15 at % of gold, silicon-germanium nitride, silicon oxide, silicon oxynitride, gallium nitride, gallium oxide, aluminum nitride, aluminum oxide, gallium aluminum nitride, or gallium aluminum oxide.

20. The method of claim **13**, wherein the ion flow is N_2^+, N^+, NO^+, NH_m^+, O_2^+, or a mixture of Ar^+ and N_2^+.

21. The method of claim **13**, wherein a curved mold of the first material is used as the curved layer of the first material deposited on the curved substrate.

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